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Multi-Band (K- Q- and E-Band) Multi-Tone Millimeter-Wave Frequency Synthesizer for Radio Wave Propagation Studies

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Abstract

This paper presents the design and test results of a multi-band multi-tone millimeter-wave frequency synthesizer, based on a solid-state frequency comb generator. The intended application of the synthesizer is in a space-borne transmitter for radio wave atmospheric studies at K-band (18 to 26.5 GHz), Q-band (37 to 42 GHz), and E-band (71 to 76 GHz). These studies would enable the design of robust multi-Gbps data rate space-to-ground satellite communication links. Lastly, the architecture for a compact multi-tone beacon transmitter, which includes a high frequency synthesizer, a polarizer, and a conical horn antenna, has been investigated for a notional CubeSat based space-to-ground radio wave propagation experiment.

1.0 Introduction

The frequency spectrum allocated and utilized currently for satellite communications uplinks and downlinks are rapidly getting congested due to very heavy usage. The logical choice is to move higher up in frequency into the millimeter-wave (mm-wave) frequency bands, which are sparsely used. The mm-wave bands include frequencies in the Q-band (37 to 42 GHz) and the E-band (71 to 76 GHz). Migrating to the mm-wave frequency bands has the added advantages of smaller antenna size and lower mass for a given spacecraft effective isotropic radiated power (EIRP). In addition, in the case of commercial communications satellites, which use multiple beams to increase throughput, the beamwidth for a given antenna aperture size is smaller at the above mm-wave frequencies. The smaller beamwidth results in a smaller spot size on ground, which allows packing a greater number of spot beams over a given area and thus enables greater spectral efficiency through frequency reuse. Prior to system planning and system design for deployment in space, it is essential to investigate the effects of Earth's atmosphere on radio wave propagation at the above frequencies. In general, radio waves suffer increasing attenuation, scintillation, depolarization, and group delay due to atmospheric gases, clouds and rain (Ref. 1).

In this paper, we present the design, construction and test results for a multi-band multi-tone millimeter-wave frequency synthesizer (Ref. 2) based on the discrete frequency spectrum produced by a high frequency solid-state comb generator. Unlike the single frequency beacon source, which flew on NASA's Advanced Communications Technology Satellite (ACTS) (Ref. 3) for Ka-band propagation experiments (Ref. 4), the multi-tone frequency synthesizer is capable of simultaneously delivering coherent multiple frequencies. These multiple frequencies enable characterizing the frequency dependent group delay effects, which are essential for the design of multi-Gbps data rate wide band satellite communications links.

2.0 Multi-Tone Frequency Synthesizer Architecture

2.1 Multi-Tone Frequency Synthesizer Circuit Design, Construction and Mode of Operation

Harmonic generators are a convenient way to generate high frequency signals, when direct generation of the high frequencies is challenging. Harmonics are generated whenever a sinusoidal signal drives a non-linear capacitance, that is the capacitance varies instantaneously with voltage or current. Such generators have become practicable because of the availability of high quality step-recovery diodes. The step-recovery diodes are also know as charge-storage or snap-back diodes. The theory of harmonic generation using step-recovery diodes can be found in Reference 5.

A simplified block schematic of the basic multi-tone frequency synthesizer based beacon transmitter that could fly on a geostationary satellite as a hosted payload for radio wave propagation experiments at mm-wave frequencies is presented in Figure 1. The synthesizer consists of a comb generator, which puts out evenly spaced harmonic frequencies of the input signal, which are coherent and tunable over a wide frequency range. These harmonics are then amplified to the power level needed for radio wave propagation studies.

Harmonics that are amplified are simultaneously transmitted as beacon signals from space to receiving ground stations located at several climate zones within the CONUS. By measuring the signal relative strength and phase at ground sites one can estimate the attenuation and group delay or dispersion due to atmospheric induced effects.

*Retired.

2.2 Rational for a Multi-Band Multi-Tone Frequency Synthesizer Circuit, Design, and Construction

Significant amount of statistical data has been accumulated since the pioneering ACTS experiments of the 1990's and accurate models that predict the impairments to radio waves in the 20/30 GHz bands due to Earth's atmosphere are available. In addition, communications satellite systems are currently operational at these frequencies. It is also well understood that signals at Q-band and E-band frequencies would experience much higher attenuation during rain fades than signals in the 20/30 GHz range. The deep fades will result in poor signal-to-noise ratio at the Q-band and E-band beacon receivers on ground, which could cause the receivers to lose frequency/phase lock. To overcome this problem it is desirable to include a coherent K-band (18 to 26.5 GHz) beacon source along with the Q-band and E-band beacon sources on the payload. Because of higher signal-to-noise ratio at K-band, the beacon receiver on ground can retain lock during deep fades and thus enable high availability attenuation measurements or characterization. This data is valuable and can provide a reference for model development and also provide an understanding of frequency model scaling factors for future system design when Q-band and E-band propagation data is unavailable (Ref. 1).

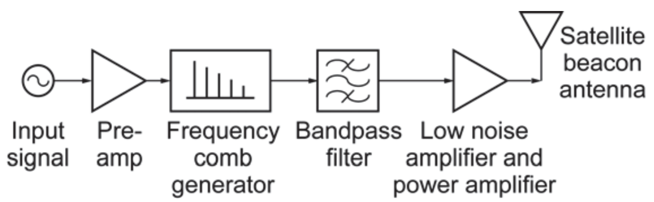


Figure 1.—Schematic block diagram of the basic multi-tone frequency synthesizer based beacon transmitter payload for radio wave propagation experiments.

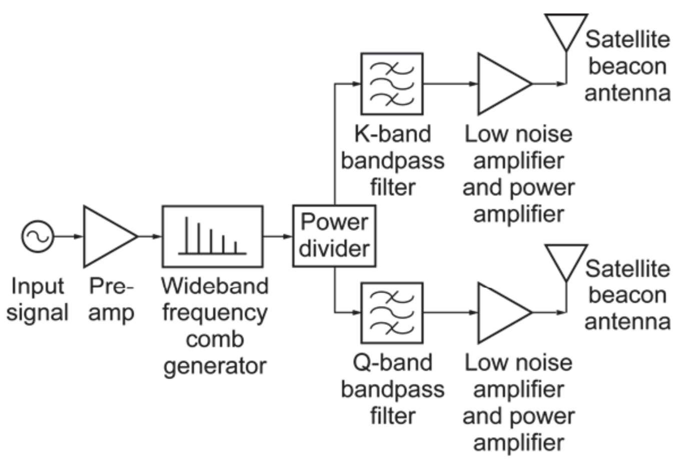


Figure 2.—Schematic block diagram of the multi-band multi-tone frequency synthesizer based beacon transmitter payload for radio wave propagation experiments.

A block schematic of the multi-band multi-tone frequency synthesizer breadboard circuit is presented in Figure 2. The synthesizer consists of a high frequency wideband solid-state comb generator. The K-band and Q-band harmonics are separated by bandpass filters and amplified to the power level required for radio wave propagation studies before transmission.

2.3 K-Band/Q-Band Multi-Tone Frequency Synthesizer Characterization and Test Data

A generic test setup for characterizing the K-band and the Q-band multi-tone frequency synthesizer circuits described above is presented in Figure 3. Photographs of the K-band and the Q-band breadboard coaxial test set up are shown in Figures 4 and 5, respectively. Notice that the set up is very compact. The bandpass filters and the low noise amplifiers (LNAs) are appropriately selected for the two frequency bands. The measured K-band and Q-band spectrums are presented in Figures 6 and 7, respectively. The tones are 1 GHz apart, but can be tuned by changing the frequency of the input signal to the frequency comb generator. Figures 8 and 9 present the results for the case when the tones are 500 MHz apart. These figures indicate that the spectrum is very distinct with excellent signal-to-noise ratio. In addition, it is worth while to point out that the K-band and Q-band multi-tones are coherent since they are derived from a common input signal source as indicated in Figure 2. A chain of MMIC based power amplifiers can further enhance the power levels such that the beacon EIRP is on the order of 30 dBW at the edge of CONUS coverage (Ref. 6). A minimum data collection period of 36 months is recommended and hence the above EIRP is the end of life value (Ref. 1).

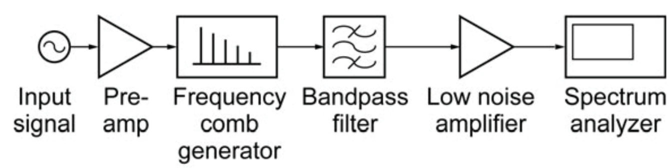


Figure 3.—Test setup for characterizing the multi-tone frequency synthesizer.

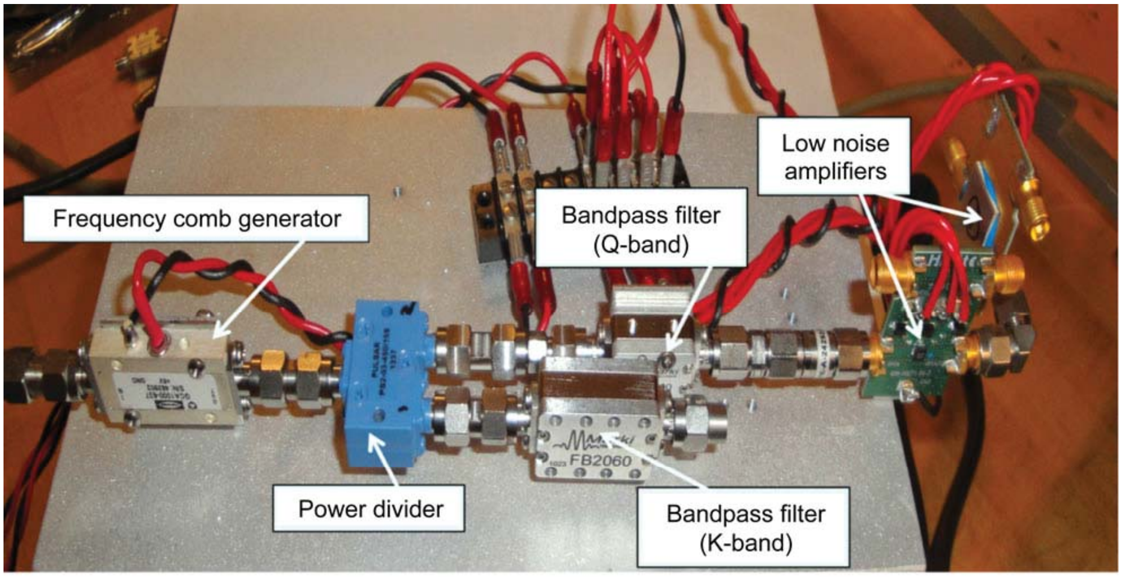


Figure 4.—Coaxial test circuit used for measurements at both K-band and Q-band.

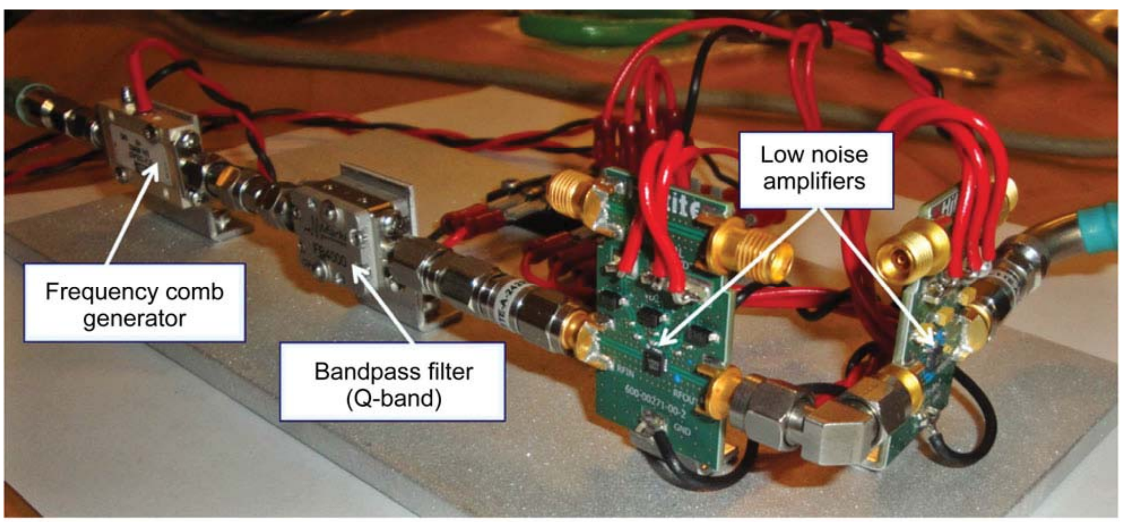


Figure 5.—Coaxial test circuit used for measurements at Q-band only.

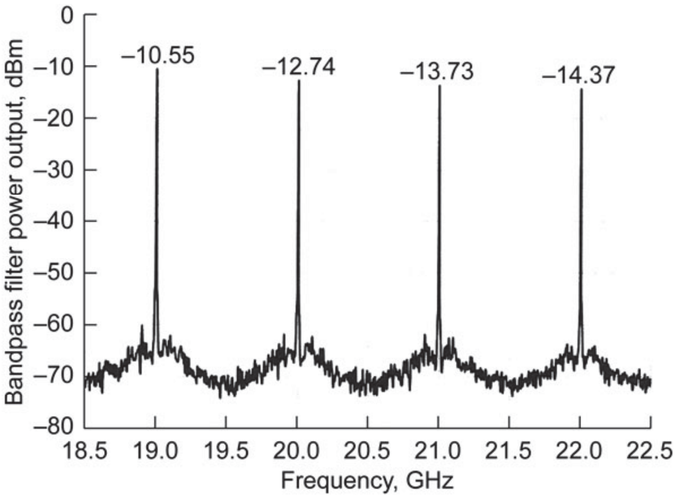


Figure 6.—K-Band multi-tones at 1 GHz intervals as measured at the output of the bandpass filter. The output power level for each tone is indicated in dBm.

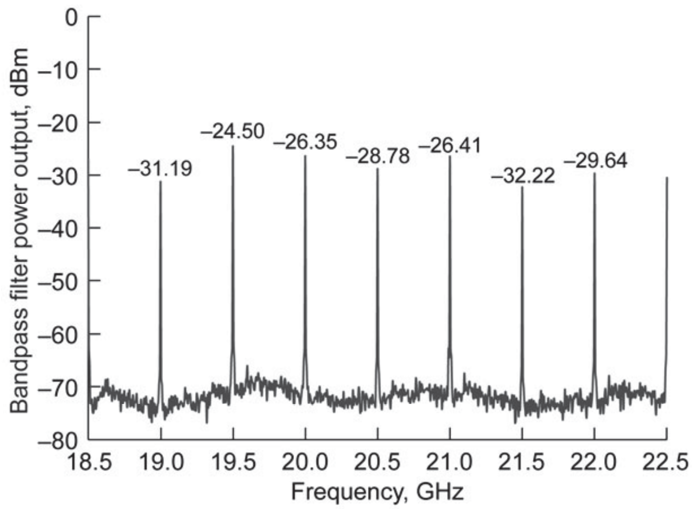


Figure 8.—K-Band multi-tones at 500 MHz intervals as measured at the output of the bandpass filter. The output power level for each tone is indicated in dBm.

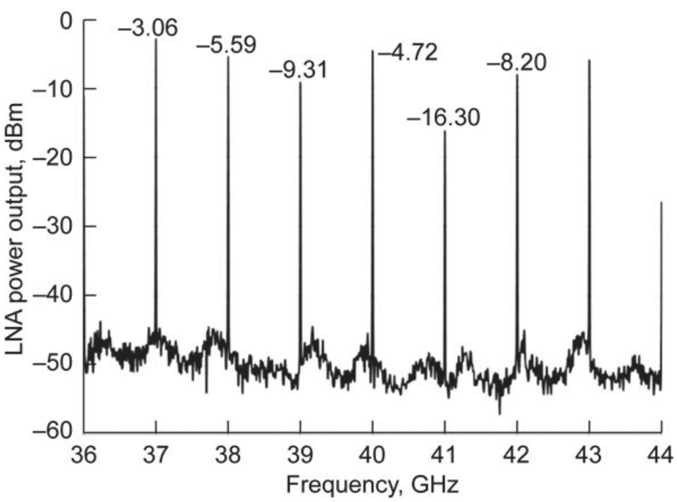


Figure 7.—Q-Band multi-tones at 1 GHz intervals as measured at the output of the low noise amplifier. The output power level for each tone is indicated in dBm.

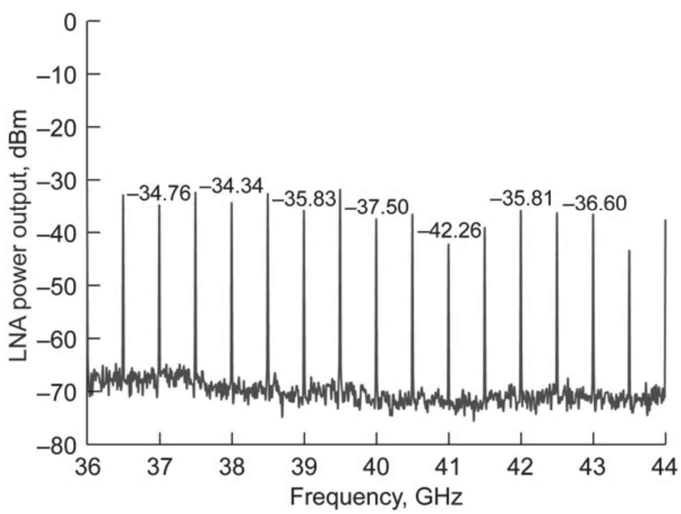
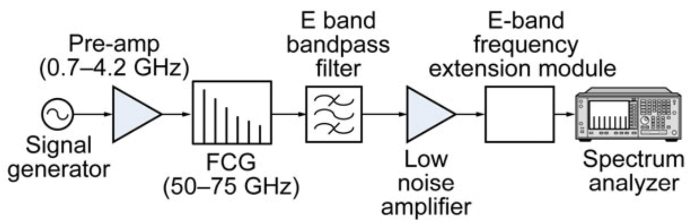


Figure 9.—Q-Band multi-tones at 500 MHz intervals as measured at the output of the low noise amplifier. The output power level for each tone is indicated in dBm.

2.4 E-Band Multi-Tone Frequency Synthesizer Characterization and Test Data

The test setup for characterizing the E-band multi-tone frequency synthesizer is presented in Figure 10. A photograph of the E-band breadboard waveguide (WR-12) test set up is shown in Figure 11. An E-band frequency extension module consisting of a harmonic mixer and a diplexer are used to extend the frequency range of the spectrum analyzer. The separation between the tones can be tuned by changing the frequency of the input signal to the frequency comb generator.

The measured E-band spectrums at the output of the low noise amplifier (LNA) are presented in Figures 12 to 14. These plots are for tones that are 1, 2, and 3 GHz apart in frequency, respectively. The corresponding amplitudes are also indicated in the figures. Notice that the tones are very distinct with excellent signal-to-noise ratio. In addition, spectrum analyzer measurements were conducted with the frequency span control set for narrow frequency range. As an example, Figure 15 presents one such tone measured at the center frequency of 70 GHz with the frequency span set equal to 100 MHz. The results indicate that the linewidth of the tone is on the order of 3 to 4 MHz close to the noise floor. A chain of MMIC power amplifiers can enhance the power of the tones to any desired level.



• Signal generator: Agilent Technologies 83640B
• Pre-amplifier: Mini-Circuits ZHL-42
• Frequency comb generator (FCG): Herotek Inc. GC2-5075W/GA
• Band pass filter: Ducommun Inc. PFB-12736040-01
• Low noise amplifier (LNA): QuinStar Technologies Inc. QLW-71764530
• Frequency extension module: OML, Inc. M12HWD with diplexer
• Spectrum analyzer: Agilent PSA E4446A with AYZ option

Figure 10.—Test setup at E-band for characterizing the multi-tone frequency synthesizer.

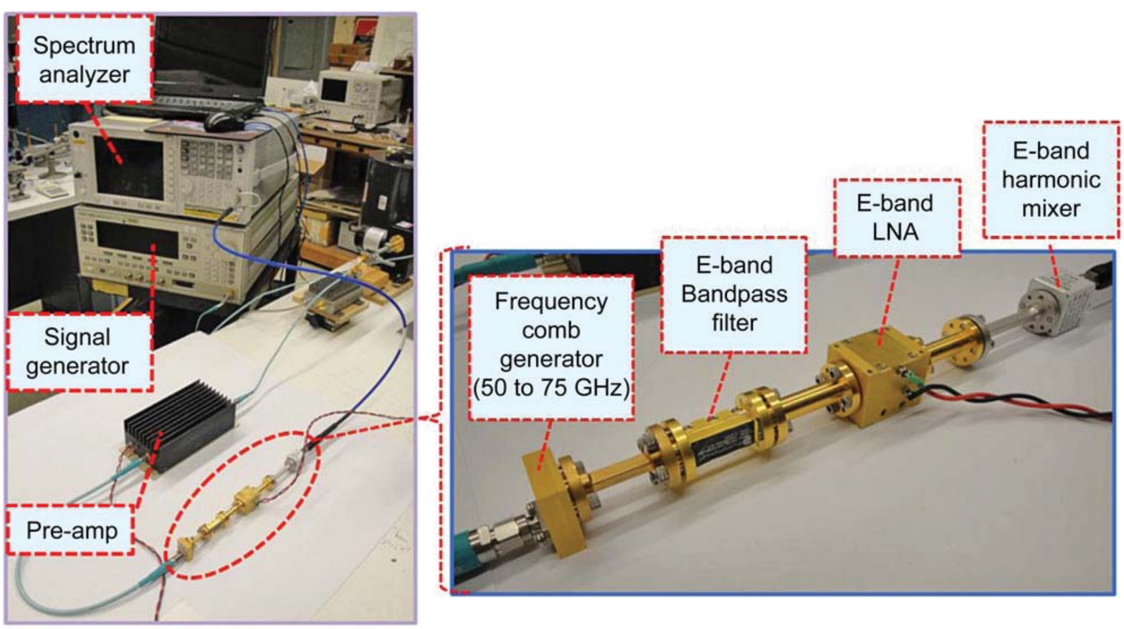


Figure 11.—E-band waveguide test setup for characterizing the multi-tone frequency synthesizer.

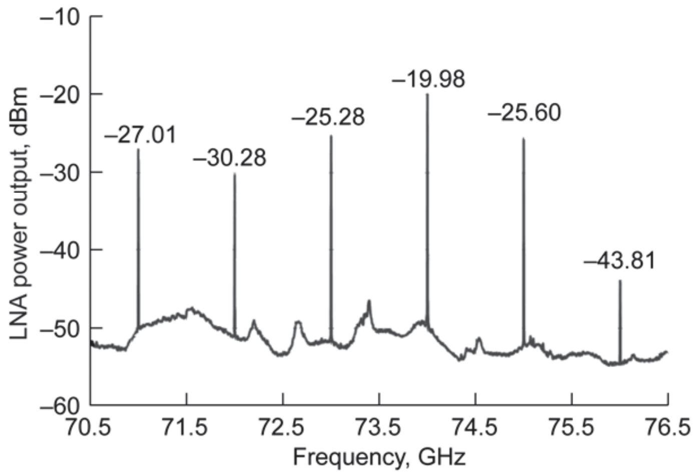


Figure 12.—E-Band multi-tones at 1 GHz intervals as measured at the output of the LNA. The output power level for each tone is indicated in dBm.

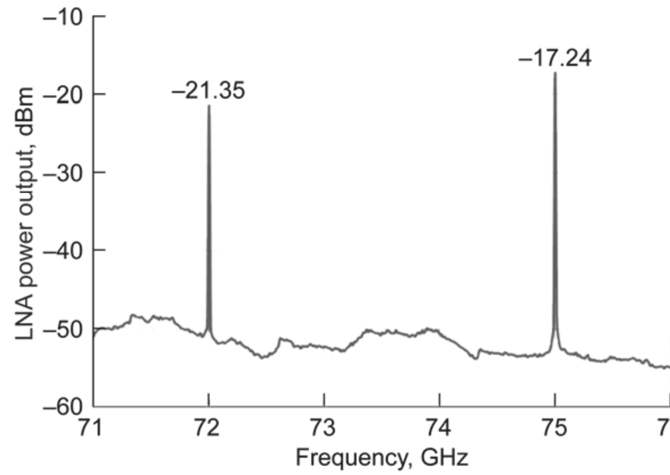


Figure 14.—E-Band multi-tones at 3 GHz intervals as measured at the output of the LNA. The output power level for each tone is indicated in dBm.

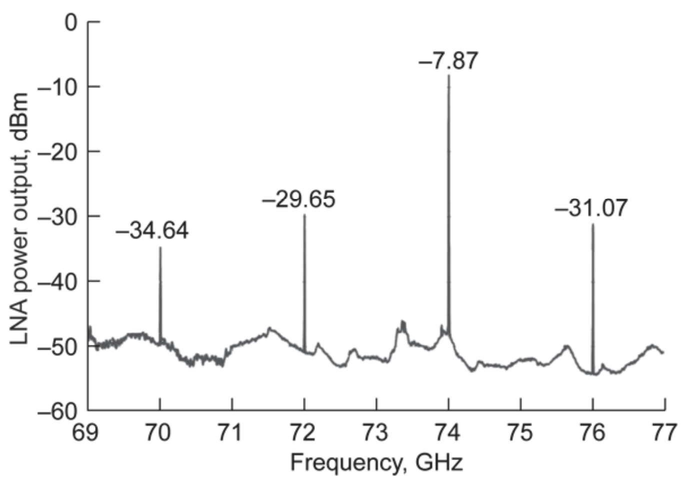


Figure 13.—E-band multi-tones at 2 GHz intervals as measured at the output of the LNA. The output power level for each tone is indicated in dBm.

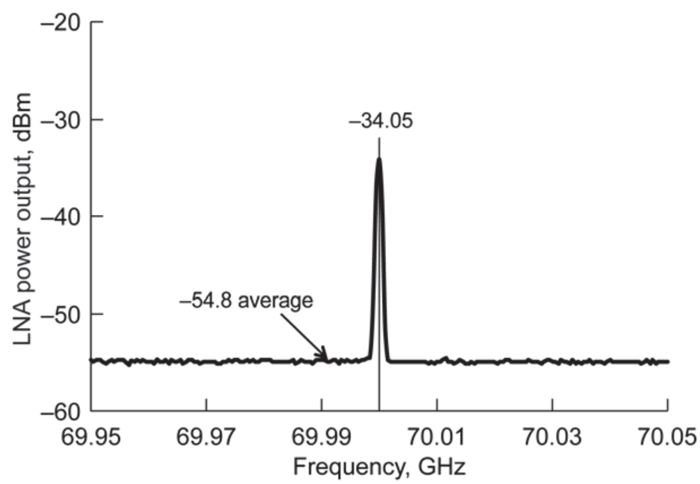


Figure 15.—Frequency spectrum of a single tone at E-band. The output power level for the tone and the noise floor are indicated in dBm.

3.0 Phase Noise Characteristics

The phase noise of the multi-tones degrades by 20 log of the multiplication factor. Hence, if we assume that the phase noise of the input signal source driving the comb generator is –152 dBc/Hz at 10 kHz offset and if the multiplication factor is 20 then the phase noise of this tone is –152 + 20 log (20), which is –126 dBc/Hz. Similarly, if the multiplication factor is 35 then the overall phase noise is –121 dBc/Hz.

4.0 Temperature Characteristics

The measurements reported here were performed at room temperature. Hence, additional studies are required to quantify the effect of temperature on the multi-tone frequency synthesizer output frequency and power.

5.0 Space Radiation Effects

Studies conducted by other researchers have indicated that the step recovery diodes are susceptible to neutron damage (Ref. 7). The degree of damage is dependent on the amount and time of exposure to neutron fluence.

6.0 E-band Multi-Tone Frequency Synthesis by Upconverting K-Band Multi-Tones

To avoid the degradation of phase noise as described above, it is possible to up convert the K-band multi-tones from the output of the wideband power divider (Fig. 2) with a mixer circuit. However, such a design has several disadvantages. First, besides a broadband mixer circuit the system also requires an additional local oscillator (LO), which makes the overall design more complex. Second, the additional components potentially increase the overall cost. Third, mixing also produces image and other spurious signals, which have to be filtered out. Lastly, if coherent K-band and E-band multi-tones are to be simultaneously transmitted then, the above LO has to be phase locked to the signal source exciting the wideband frequency comb generator (Fig. 2), which further increases the complexity and cost.

7.0 Notional CubeSat Space Experiment Package

A basic multi-tone beacon transmitter chain, which includes a high frequency synthesizer, a polarizer, and a conical horn antenna has been configured and illustrated in Figure 16. The transmitter chain is compact enough to be accommodated inside a 1U CubeSat as illustrated in Figure 17. The CubeSat architecture is being investigated for a notional space-to-ground radio wave propagation experiment.

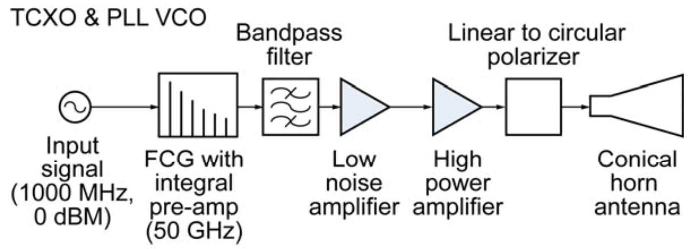


Figure 16.—Basic multi-tone synthesizer circuit configuration for a notional CubeSat space experiment.

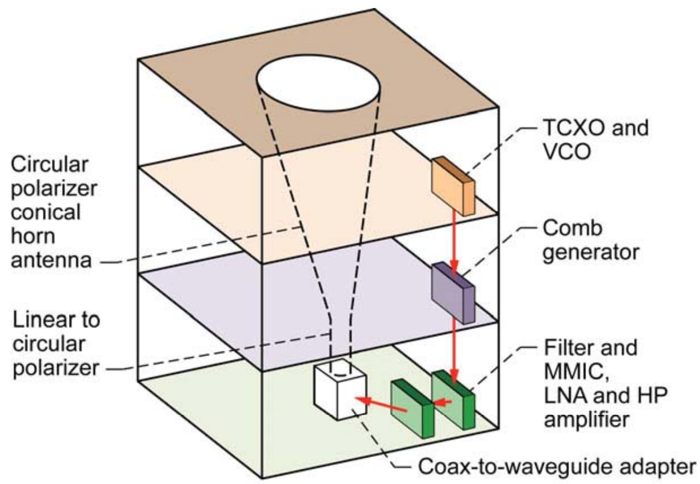


Figure 17.—Beacon transmitter chain accommodated inside a CubeSat for a notional space-to-ground radio wave propagation experiment. For simplicity, prime power conditioning and other control circuitry has been omitted.

8.0 Conclusions

The design, construction and test data for a K-band, Q-band, and E-band multi-tone frequency synthesizer for radio wave propagation studies are presented. The tones in each of the above bands are very distinct with excellent signal-to-noise ratio. The beacon transmitter will enable characterizing the frequency dependent group delay effects, which are essential for the design of multi-Gbps data rate wide band satellite communications links.

Lastly, a simplified layout for a compact multi-tone beacon transmitter for a notional CubeSat based space-to-ground radio wave propagation experiment has been presented. Besides, radio wave propagation studies, the multi-tone frequency synthesizer can be used for space borne active remote sensors like scatterometers, which require coherent, highly stable multi frequency signals.

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